

The Kinematics of the Outer Halo of M87¹

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ABSTRACT

Radial velocities are presented for a new sample of globular clusters in the outer halo of M87 at a distance of 300 to 540 arcsec (24 to 43 kpc) from the center of this galaxy. These are used to augment our previously published data and an analysis of the rotation and velocity dispersion of the M87 globular cluster system is carried out. The rotation is $\sim 300 \text{ km s}^{-1}$ at $R = 32 \text{ kpc}$, at which point the velocity dispersion is also still quite high, $\sim 450 \text{ km s}^{-1}$. The high rotation is interesting. The outer halo of M87 is, as was found in our previous kinematic analysis, very massive.

Subject headings: galaxies: individual (M87) — galaxies: fundamental parameters — galaxies: star clusters

1. Introduction

Cohen & Ryzhov (1997) (henceforth CR) present an analysis of the kinematics of M87 based on radial velocities for 205 globular clusters (henceforth GCs) in the halo of M87. In that paper we adopted a rotation curve which rises linearly with radius from the center of M87 (R) until reaching 180 km s^{-1} at a radius of 225 arcsec. Beyond that point, and particularly beyond $R \sim 350 \text{ arcsec}$, our sample became too sparse to establish a meaningful rotation curve, and, following the example of the Galaxy, we adopted the fixed value of 180 km s^{-1} as the rotation of the outer part of M87.

The rotation of M87 is important for two reasons. The total angular momentum of M87 is a clue to the mode of formation of this massive elliptical galaxy at the center of the Virgo cluster cooling flow. This parameter can help distinguish between formation via a gravitational collapse as advocated by Peebles (1969) as compared to a merger model. In addition, a major goal of CR was the determination of the enclosed mass of M87 as a function of R . A proper dynamical mass estimate requires knowledge of both rotation and dispersion.

Kissler-Patig & Gebhardt (1998) suggested, based on a reanalysis of our previously published data, that the rotation in the outer part of M87 is large and decreases the observed σ_v more than

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we allowed for in our previous work. Since our sample of GCs there is very sparse, the purpose of this paper is to present radial velocities for an additional group of M87 globular clusters selected to be in spatial positions which maximize their ability to constrain the rotation of the outer halo of M87. We then combine this new data with our previously published data to re-examine the issue of the rotation and velocity dispersion in the outer part of M87.

Whitmore *et al.* (1995) derive a distance to M87 of 17 Mpc from the turnover of the M 87 GC luminosity function. This is in excellent agreement with the mean of the Cepheid distances for Virgo cluster spirals from Pierce *et al.* (1994) and from Ferrarese *et al.* (2000) of 16 Mpc, ignoring NGC 4639 (Saha *et al.* 1996) as a background object. Hence we adopt 16.3 Mpc (80 pc/arcsec) as the distance to M87.

2. New Observations of M87 GCs

We observed a single slitmask of M87 GC candidates with the Low Resolution Imaging Spectrograph (henceforth LRIS) (Oke *et al.* 1995) at the Keck Telescope during the spring of 1999. This mask was designed to include objects located along the major axis of M87 ≈ 400 arcsec SE of the nucleus, with the slit length running perpendicular to the major axis. It contains objects with $R \sim 300$ to 540 arcsec from the center of M87. Candidates from the catalog of Strom *et al.* (1981) in this area were checked on existing direct images to determine if they appeared to be M87 GCs. Those that are brighter than $B = 22$ mag and that were not observed by CR were included here. In addition, our new sample is at the maximum radius from M87 of the Strom *et al.* survey. Since we wish to include M87 GCs at even larger radii, we selected several stellar objects from the area on these LRIS images beyond that of the Strom *et al.* survey which appeared to be M87 GCs. Finally, we included the object in this region with the most discordant v_r from CR.

The slitmask was observed with the same instrumental configuration of LRIS as was used in CR, but the grating was tilted to center the spectra at $H\alpha$. Only $H\alpha$ was used to determine the radial velocities. Because of the plethora of night sky lines and the use of a 1 arcsec wide slit, these v_r are more accurate than those of CR, with typical 1σ errors of only ± 50 km s $^{-1}$. Table 1 lists the new radial velocities. There are 20 entries, four of which are included in CR. Two of the M87 GCs were found through the procedure described above and have not been previously cataloged. They are assigned identifying numbers beginning with 6000; their location and brightness in the R filter bandpass using the standard stars of Landolt (1992) are given in footnotes to the table. Both are more than 500 arcsec from the center of M87.

The v_r from CR for the four cases in common are given in the last column of Table 1. The agreement is very gratifying and suggests yet again that the quoted error estimates for these GC radial velocities are realistic.

Several interlopers were also found among these new spectroscopic observations. Strom 81 is a galaxy showing strong $H\alpha$ emission with $z = 0.335$, and Strom 87, 221 and 286 are galactic stars.

3. Rotation and Velocity Dispersion Analysis

The sample of 16 new GCs in M87 presented in Table 1 more than doubles the sample with spectroscopic v_r with $R > 420$ arcsec. This should produce credible measures of the rotation and velocity dispersion in the outer part of M87. The sample of M87 GC radial velocities we utilize below is that of CR as augmented and updated in Cohen, Blakeslee & Ryzhov (1998) plus the new material presented in Table 1. This gives a total of 222 objects believed to be M87 GCs.

3.1. Qualitative Results

To demonstrate in a simple yet convincing manner that significant rotation exists in the outer halo of M87, we assume that the rotation is about a fixed position angle, that characteristic of the isophotes of M87. A modern study of the isophotes of M87 by Zeilinger, Moller & Stiavelli (1993) finds the major axis of the galaxy to be at $PA = 160^\circ$ and the effective radius to be ~ 90 arcsec (7.2 kpc). The ellipticity they deduce increases with radius outside the core, reaching 0.2 at $1.3r_{eff}$. (In early work on this galaxy, Cohen 1986 found $\epsilon \sim 0.2$ at $R = 230$ arcsec with a position angle of 155° .) McLaughlin, Harris & Hanes (1994) establish that the PA of the M87 GC system is identical to that of the underlying galaxy halo light. Kundu *et al.* (1999) find the PA of the globular cluster system very close to the center of M87 to be somewhat larger, $\sim 190^\circ$. The analysis of the isophotes of this galaxy by Blakeslee (1999) covers this entire range of R and shows the twisting of their major axis within the central 20 arcsec and the increase of ϵ outward.

We further assume that the mean velocity at all radii is the systemic velocity of M87, 1277 ± 5 km s $^{-1}$ (van der Marel 1994). Figure 1 shows the rotation curve deduced under these assumptions for all M87 GCs beyond $R = 380$ arcsec with separate symbols for the new observations presented here and for the published data of CR. The horizontal line indicates the systemic velocity while the curve shown is for $v_{rot} \sin(i) = 300$ km s $^{-1}$. The sample at such large distance from the center of M87 is now reasonably large (31 M87 GCs) with good coverage near $PA = 160$ and 340° , i.e. along the major axis both towards the SE and the NW from the center of M87, and clearly demonstrates that the outer part of M87 is rotating rapidly. In addition, Figure 1 shows that the velocity dispersion of the M87 GC system is still very large, ~ 400 km s $^{-1}$, even at the outermost point reached.

3.2. Quantitative Determination of the Rotation Curve of M87

Both the analysis given in CR and that of Kissler-Patig & Gebhardt (1998) suggest that the assumptions made above with respect to the position angle of the axis of rotation and the systemic velocity are correct, and we therefore adopt them for our detailed analysis of the rotation of M87.

GCs that are located on the minor axis constrain the mean velocity and velocity dispersion but

contribute no information towards determining the amplitude of rotation. Having made the above assumptions, given the large velocity dispersion of the M87 GC system compared to the expected rotation, the GCs near the minor axis of M87 contribute mostly noise to the determination of the amplitude of rotation. We thus do not include clusters with $|\cos(\theta - \theta_0)| < 0.30$ in the rotation solution, the choice of angle being somewhat arbitrary but based on the ratio of σ_v/v_{rot} . This excludes GCs in two arcs, each 35 deg long, centered on each end of the minor axis, or 19% of the total sample, if the GCs are distributed uniformly in angle at all radii. All GCs, including the ones rejected here, are subsequently utilized to determine the velocity dispersion.

The rotation analysis is thus reduced to finding a suitable statistically accurate representation of the set of values $\{v_{rot}(R)\}_i = (v_r(i) - v_{sys})/\cos(\theta - \theta_0)$ for GCs within a specified range of R . Within each radial bin considered, a two step χ^2 minimization solution was implemented to solve for an appropriate value of the amplitude of the rotation, $v_{rot}(R)$. The errors in the individual terms on the right hand side of the above expression for a constant observational uncertainty in v_r are highly variable and depend on θ . The procedure adopted allows for these varying uncertainties. In the first pass, an initial guess at $\sigma_v(R)$ is used, and a solution for $v_{rot}(R)$ is found. This solution for $v_{rot}(R)$ is used to derive $\sigma_v(R)$. Since $\sigma_v(R)$ is used as the error estimate for each point for $v_{rot}(R)$, a second pass solution, which only makes very small updates, is then carried out to derive $v_{rot}(R)$.

The GCs in the spectroscopic sample are sorted in ascending order in R . The analysis is carried out with 30 point bins at the extreme inward and outward points, increasing to bins with 50 GCs wherever possible. The bin center is shifted outward by 1 GC, and the solution is repeated. Figure 2 displays the resulting solution for $v_{rot}(R_m)$ as a function of the median distance R_m from the center of M87 for the GCs in each bin. The errors are calculated assuming Gaussian statistics within each bin. The radial extents for a few typical bins are indicated by the horizontal lines in the Figure. The rotation curve is heavily oversampled; there are only five independent points on this Figure.

3.3. Determination of the Velocity Dispersion

The calculation of the velocity dispersion requires removal of the rotational velocity. This is done using a smoothed version of the rotation amplitude found as described above. The biweight estimator described in Beers, Flynn & Gebhardt (1990) which is strongly resistant to outliers is used. The instrumental contribution to $\sigma_v(R)$ is also removed in quadrature. The same variable binning with R used for the rotation solution is adopted here. The entire spectroscopic sample of M87 GCs is used.

The resulting radial profile of σ_v is shown in Figure 2. The radial extent of a few typical bins is indicated by the horizontal lines in the Figure. As is the case for Figure 1, the velocity dispersion profile shown in this Figure is heavily oversampled.

4. Discussion

4.1. Comments on Galaxy Formation

Both the qualitative and the quantitative analysis show that the outer part of the halo of M87 with $R \sim 400$ arcsec, 32 kpc from the center of M87 and at $4.4r_{eff}$, is rotating with a projected rotational velocity of $\sim 300 \text{ km s}^{-1}$. This is a very large rotational velocity to be found so far out in M87, implying that the total angular momentum of M87 is very large. It is interesting to note that the halo population of the Galactic globular cluster system shows a rotation of only $50 \pm 23 \text{ km s}^{-1}$ while the disk population of Galactic GCs is highly flattened with $v_{rot} 152 \pm 29 \text{ km s}^{-1}$ (Zinn 1985).

Among the various theories of galaxy formation, there are several that are often applied to elliptical galaxies. The theory of dissipationless collapse from a single gas cloud through a gravitational instability, and acquisition of angular momentum through tidal torques was worked out by Peebles (1969). Binney (1978) calculated the expected rotation velocities of elliptical galaxies under various assumptions regarding orbit anisotropy. Detailed N-body simulations along these lines have been carried out by several groups, including Barnes & Efstathiou (1987), Stiavelli & Sparke (1991) and Ueda *et al.* (1994). The relevant parameter for comparison of observations with analytical and numerical models of galaxy formation is the spin parameter (Peebles 1971), a dimensionless combination of the total angular momentum, total mass, and total energy for a galaxy, $\lambda = JE^{1/2}G^{-1}M^{-5/2}$. This does not exceed 0.1 for such models, while Kissler-Patig & Gebhardt (1998) find $\lambda \sim 0.18$ for M87, with the caution that calculating λ from our existing observational material requires an extrapolation to the half mass radius in the halo of M87, much further out in R . The complication of possible triaxial shapes rather than oblate isotropic rotators, reviewed by de Zeeuw & Franx (1991), further obscures the validity of such calculations.

The other major theory currently in vogue for the formation of elliptical galaxies is through the merger of several large gas rich fragments, as originally suggested by Toomre & Toomre (1972). Such models come in various flavors, with the mergers happening relatively late and the pieces being entire galaxies as in Kormendy (1989) and Kormendy & Sanders (1992) or happening at early times involving protogalaxy clumps as in White & Rees (1977). Recent numerical simulations of this type of model, expanding on the earlier work of Barnes (1988), can be found in Hernquist & Bolte (1993) and in Bekki (1998). It is likely that such a model is more capable of reproducing the high rotation we find. Furthermore the observation of non-symmetric diffuse light in the halo of M87 extending 100 Kpc from its center by Weil, Bland-Hawthorn & Malin (1997) may also be explained by the recent accretion of a low mass galaxy.

4.2. The Effect of the Present Results on Those of Cohen & Ryzhov (1997)

Even with the large rotation we have found in the outer part of M87, we find the velocity dispersion after the observed values are corrected for the rotation to be still high there. σ_v in the outermost bin of CR agrees to within 5% with the value found here. Only in one of the the nine radial bins used by CR is σ_v from the current solution smaller than the values given in CR. We therefore expect that the results of CR with respect to the distribution of mass within M87 still are approximately correct.

5. Summary

We have presented spectroscopic observations of a new sample of M87 GCs chosen to put maximum leverage on a determination of the rotation in the outer halo of M87. Using this data combined with our previously published data we find that the rotation of M87 increases outward and reaches a value of $\sim 300 \text{ km s}^{-1}$ at a distance of 400 arcsec (32 kpc, $4.4 r_{eff}$) from the center of this galaxy, confirming the suggestion based on our previously published set of M87 GC radial velocities by Kissler-Patig & Gebhardt (1998) of high rotation. That is rather surprising. The velocity dispersion remains high even at that large R , and the enclosed total mass is very large, as our earlier work (see CR) suggested.

The high rotation may provide a clue to the mode of formation of M87, but the calculation of total spin is uncertain as it involves extrapolation to still larger radii. In addition, M87 is located in a very special place, the center of a very large mass concentration, a large cooling flow, etc. Its history may be quite different from that of most ellipticals, even of most massive ellipticals.

The results of the initial spectroscopic studies of the dynamics of elliptical galaxies in the early 1980s were very surprising. Davies *et al.* (1983) showed that low luminosity ellipticals rotate as rapidly as spiral bulges and as rapidly as predicted by models with oblate figures and isotropic distributions of residual velocities. However, as was discovered by Illingworth (1977), high luminosity ellipticals show surprisingly small values of v_{rot}/σ_v . Our results for the outer part of M87, where $v_{rot}/\sigma_v \sim 0.6$, include no correction to v_{rot} for projection effects, which would only make this ratio larger. Similar suggestions for high rotation in the outer parts of luminous ellipticals near the center of large clusters of galaxies have been obtained from the analysis of a sample of globular clusters in M49 by Sharples *et al.* (1998) and one in NGC 1399 by Kissler-Patig *et al.* (1999). This gives rise to some interesting questions. Is this large rotation in the outer parts of the M87 GC system also shared by the M87 stellar halo ? How far out does this rotation continue ? To be provocative, we might ask if most luminous elliptical galaxies have $v_{rot}/\sigma_v > 0.5$ in their outer parts, and whether this was missed in earlier studies due to limitations on slit length and on surface brightness in those spectroscopic studies ?

One of the few ways to explore these issues is to attempt to find large samples of GCs even

further out in the halo of M87. We have paved the way with a first identification of M87 GCs beyond the spatial limit of existing surveys.

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REFERENCES

- Ashman, K.M. & Zepf, S.E., 1998, “Globular Cluster Systems”, Cambridge University Press
- Barnes, J., 1988, ApJ, 331, 699
- Barnes, J. & Efstathiou, G., 1987, ApJ, 319, 575
- Bekki, K., 1998, ApJ, 496, 713
- Beers, T. C., Flynn, K. & Gebhardt, K., 1990, AJ, 100, 32
- Binney, J., 1978, MNRAS, 183, 501
- Blakeslee, J.P., 1999, private communication
- Cohen, J.G., 1986, AJ, 92, 1039
- Cohen, J.G., Blakeslee, J.P. & Ryzhov, A., 1998, ApJ, 496, 808
- Cohen, J.G. & Ryzhov, A. (CR), 1997, ApJ, 486, 230
- Davies, R.L., Efstathiou, G., Fall, S.M., Illingworth, G. & Schechter, P.L., 1983, ApJ, 266, 41
- Ferrarese, L., *et al.* 2000, ApJ, in press
- Hernquist, L. & Bolte, M., 1993, in “The Globular Cluster-Galaxy Connection”, ed. H.Smith & J.Brodie, ASP Conference Series 48, 789
- Kissler-Patig, M. & Gebhardt, K., 1998, AJ, 116, 2237
- Kissler-Patig, M., Grillmair, C. J., Meylan, G., Brodie, J. P., Minniti, D. & Goodfrooij, P., 1999, AJ, 117, 1206
- Kormendy, J., 1989, ApJ, 342, L63
- Kormendy, J. & Sanders, D.B., 1992, ApJ, 390, L53
- Kundu, A., Whitmore, B.C., Sparks, W.B. & Duccio Machetto, F., Zepf, S.E. & Ashman, K.M., 1999, ApJ, 513, 733
- Illingworth, G., 1977, ApJ, 218, L43
- Landolt, A. U., 1992, AJ, 104, 340
- McLaughlin, D.E., Harris, W.E. & Hanes, D.A., 1994, ApJ, 422, 486
- Oke, J.B., J.G.Cohen, M.Carr, J.Cromer, A.Dingizian, F.H.Harris, S.Labrecque, R.Lucinio, W. Schaal, H.Epps & J.Miller, 1995, PASP, 107, 307
- Peebles, J., 1969, ApJ, 155, 393
- Peebles, J., 1971, α , 11, 377
- Pierce, M., Welch, D. L, McClure, R. D., VandenBergh, S., Racine, R. & Stetson, P. B., 1994, Nature, 371, 385
- Saha, A., Sandage, A., Labhardt, L., Tammann, G. A., Macchetto F. D. & Panagia, N., 1996, ApJ, 466, 55

- Sharples, R. M., Zepf, S. E., Bridges, T. J., Hanes, D. A., Carter, D., Ashman, K. M. & Geisler, D., 1998, *AJ*, 115, 2337
- Stiavelli, M. & Sparke, L.S., 1991, *ApJ*, 382, 466
- Strom, S.E., Forte, J., Harris, W., Strom, K.M., Wells, D., & Smith, M. 1981, *ApJ*, 245, 416
- Toomre, A. & Toomre, J., 1972, *ApJ*, 178, 623
- Ueda, H., Shimasaku, K., Sugimotohara, T. & Suto, Y., *PASJ*, 46, 319
- van der Marel, R.P., 1994, *MNRAS*, 270, 271
- Weil, P., Bland-Hawthorn, J. & Malin, D., 1997, *ApJ*, 490, 664
- White, S.D.M. & Rees, M.J., 1978, *MNRAS*, 183, 341
- Whitmore, B.C., Sparks, W.B., Lucas, R.A., Duccio Machetto, F. & Biretta, J.A., 1995, *ApJ*, 454, L73
- Zeilinger, W.W., Moller, P. & Stiavelli, M., 1993, *MNRAS*, 261, 175
- Zinn, R., 1985 *ApJ*, 293, 424

Table 1. New Radial Velocity Measurements for M87 Globular Clusters

ID ^a	R^b (arcsec)	v_r (km s ⁻¹) (± 50 km s ⁻¹)	v_r from CR (km s ⁻¹) (± 100 km s ⁻¹)
16	530	1115	
28	494	1157	
41	486	1814	
66	517	2212	2260
77	367	1774	
94	393	963	
103	375	1092	
137	367	1764	
176	502	2167	2210
177	479	1540	1629
300	455	1977	
314	309	1167	1236
379	413	2244	
415	395	1817	
477	363	1584	
514	412	1617	
603	397	1741	
731	383	960	
6003 ^c	516	1741	
6004 ^d	540	1741	

^aID from Strom *et al.* (1981) except as noted.

^bDistance from the center of M87.

^cNew M87 GC located 2.7 arcsec W and 27.3 arcsec S of Strom 176, $R = 21.05$ mag

^dNew M87 GC located 1.2 arcsec W and 54.4 arcsec S of Strom 176, $R = 21.22$ mag

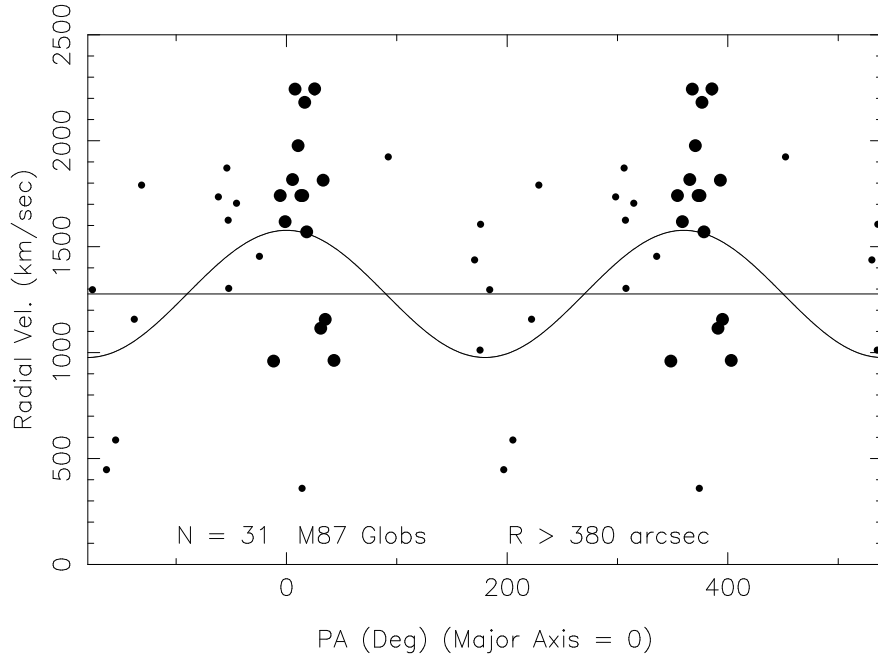


Fig. 1.— The radial velocity of M87 GCs with $R > 380$ arcsec is shown as a function of position angle about the major axis of M87. The large filled circles are from the data of Table 1, while the smaller filled circles represent M87 GCs from CR. The curve shows the projected rotation as a function of θ with amplitude of 300 km s^{-1} about the systemic velocity (indicated by the horizontal line).

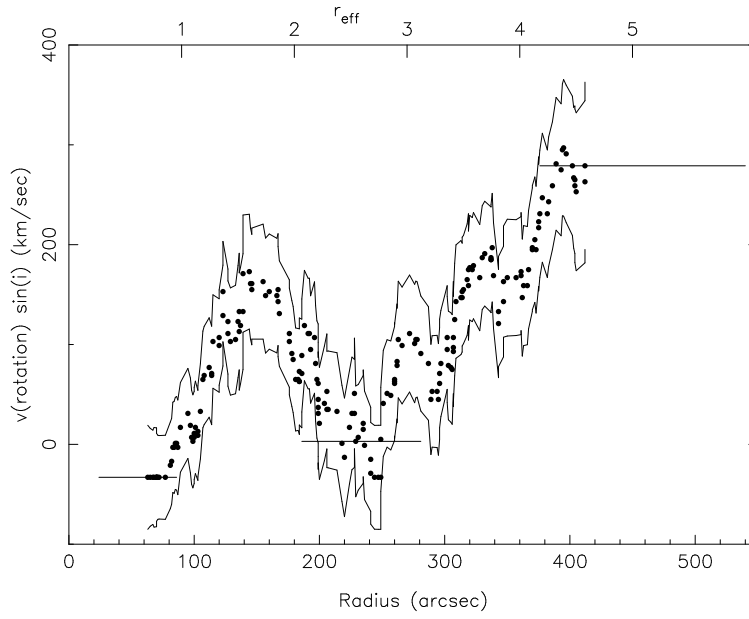


Fig. 2.— The projected rotational velocity inferred for M87 from its system of GCs is shown as a function of R . Each point represents a group of GCs at similar radii. The range of radii included within three typical bins are indicated by the horizontal lines. The 1σ error bars for each point are also indicated by the lines. Details of the binning scheme are described in the text.

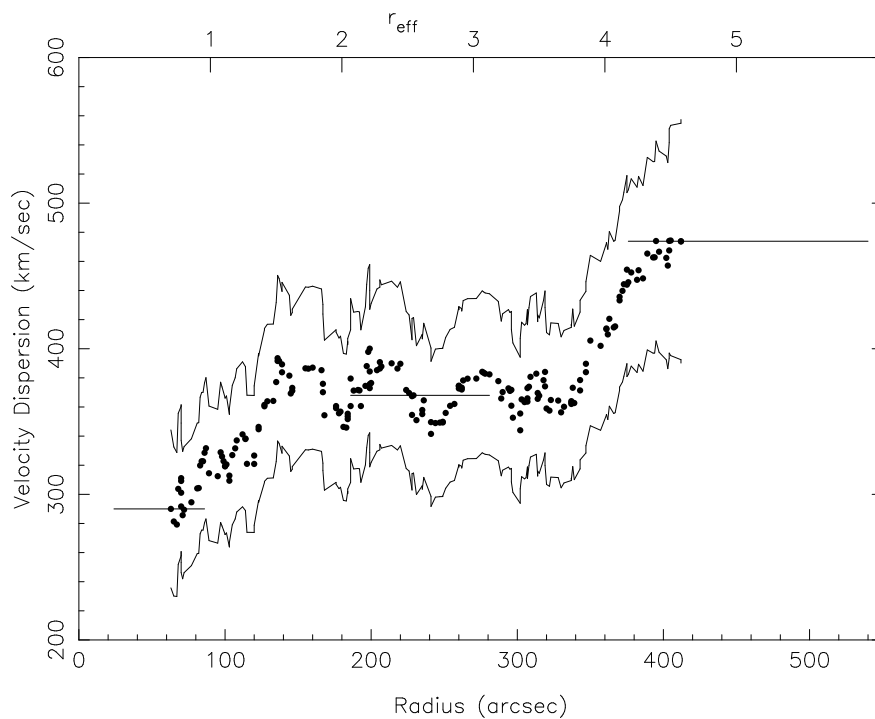


Fig. 3.— The same as Figure 2 for the velocity dispersion. The contribution of rotation to the observed σ_v has been removed.